

OPTIMIZATION OF ABRASIVE WATERJET MACHINING PROCESS PARAMETERS USING ORTHOGONAL ARRAY WITH GREY RELATIONAL ANALYSIS

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ABSTRACT

In the present work, the optimization of the abrasive water jet machining (AWJM) process parameters with multiple performance characteristics based on the orthogonal array with the grey relational analysis (GRA) has been studied. Optimization of multiple response characteristics is far more complex compared to optimization of single performance characteristic. A grey relational grade (GRG) calculated based on grey relational analysis is used to optimize the AWJM process with the multiple performance characteristics. In the present study, four machining parameters, namely hydraulic pressure, abrasive mass flow rate, standoff distance and traverse rate are optimized with consideration of multiple performance characteristics viz., surface waviness at four different heights of a Kevlar composite laminate. Experimental results have shown that machining performance in the AWJM process can be improved effectively using this approach.

Keywords: AWJM; Kevlar composite; Orthogonal array; Grey relational analysis, Surface waviness.

INTRODUCTION

Abrasive water jet machining (AWJM) process is one of the non-traditional machining processes that have been used extensively in various industry related applications. The basic principles of abrasive water jet machining (AWJM) were reviewed in details by Momber and Kovacevic 1992. This technology is less sensitive to material properties as it does not cause chatter, has no thermal effects, impose minimal stresses on the workpiece, and has high machining

versatility and high flexibility. But it has some drawbacks; especially it may generate loud noise and a messy working environment (Wang and Wong 1999).

The use of composite materials becomes prominent in today's modern technological applications. These materials have better mechanical properties such as low densities, high strength, stiffness and abrasion, impact and corrosion resistances. The creation of aramid fibres called Kevlar has led to the big breakthrough in the development of modern ballistic armour due to its unique properties of special application in armour which give ballistic protection (Komanduri et al. 1991). It has unique characteristics such as high strength to weight ratio, high chemical resistance, high cut resistance, flame resistance and good corrosive resistance (Komanduri et al. 1991).

Machining of AFRP composites requires the need for better understanding of cutting processes regarding accuracy and efficiency. Moreover, due to the anisotropic and non homogeneous nature of composites, their machining behaviour differs in many aspects from metal machining. In conventional machining processes notably drilling is the most frequently employed machining operation of composite materials. Drilling of composite laminates causes more wear of the drill compared to drilling on conventional materials mainly due to heterogeneity of the work material which leads the drill bit to experience variable forces resulting in damage of work material such as delamination, fibre pull out and poor hole quality (Ramkumar et al. 2004). Due to these limitations of conventional machining processes, alternative techniques that utilize non-conventional energy sources for material removal such as electrical discharge machining (EDM), laser cutting, ultrasonic machining, waterjet and abrasive waterjet machining has drawn much interest and has been studied the feasibility of the processes (Komanduri et al. 1991). Among these non-conventional machining processes, abrasive waterjet machining is the only method used in industry today for trimming fibre reinforced composite materials as laser machining suffers from the problem of a large heat-affected zone, while EDM suffers from extremely low cutting rates.

In the present study, the orthogonal array and grey relational analysis is used to optimize multiple performance characteristics of surface waviness at four different depth cuts. Through the grey relational analysis, a grey relational grade is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade.

EXPERIMENTAL WORK

MATERIAL

In present study, Kevlar 129 was used and hand laminated in the prepreg form of modified phenolic resin having its real weight of 410 g/m². The aramid fibres which was readily available in a woven fabric and named for its manufacture's style of 258 (2x2 basket weave) were used for the preparation of the laminates. The fibre fabrics were cut into squares of 300 mm x 300 mm. The layers were properly stacked into 22 plies. The laminates were cured at a pressure of

approximately 80 kg/cm² in a 100 tons Wabash hot press. The actual thickness of the laminate was 9.2 mm. The volume fraction of the laminate is around 54%. The orientation of fibre within the fabric was kept constant all the time during lay-up process hence they are considered as bidirectional laminates [0°/90°]. The fibre filament has a diameter of 12 µm. The mechanical properties of Kevlar 129 are given in Table 1.

Table 1: Mechanical properties of Kevlar 129 (Yang 1993)

Density (g/cm ³)	Ultimate Tensile Strength (GPa)	Tensile Elongation (%)	Tensile Modulus (GPa)	Max, Use Temp. (°C)
1.45	3.4	3.3	99	250

EQUIPMENT

The equipment used for machining the samples was Excel-CNC abrasive waterjet cutting machine equipped with Ingersold Rand model of water jet pump with the designed pressure of 345 MPa (50,000 psi). The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a workpiece table with dimension of 1200 mm x 2400 mm. For the nozzle assembly, it has an orifice of 0.25 mm diameter of sapphire jewel and a focusing tube of 0.76 mm internal diameter of carbide with a focus length of 70 mm. Throughout the experiments, the nozzle was frequently checked and replaced with a new one if the nozzle was worn out significantly. All experiments were conducted using garnet as the abrasive with mesh size of #80 (≈ 177 µm). This size was selected due to its most applications in industrial operations of abrasive water jet machining.

EXPERIMENTAL DESIGN

In the present study, six machining parameters were selected as control factors as shown in Table 2. The parameters and levels were selected primarily based on the literature review of some studies that had been documented on AWJ machining on Kevlar composite (Rahmah et al. 2003), ceramic materials (Chen et al. 1995), metallic coated sheet steels (Wang and Wong 1999) and fibre-reinforced plastics (Azmir and Ahsan 2007). The L₁₈ orthogonal array (OA) for the machining parameters is given in Table 3. Since the OA contains eight columns, only four columns were used to accommodate four machining parameters. The remaining four columns have been left unused to estimate experimental error.

For each experimental run, the machining parameters were set to the pre-defined levels according to the orthogonal array. Squares of 20 mm × 20 mm of the test specimens were cut out with full penetration as shown in Figure 1. All machining procedures were done using a single-pass cutting. Some of the machining parameters were kept constant during the experiments. These parameters are water-orifice diameter of the nozzle (0.01 inch ≈ 0.254 mm), impact angle (90°), focusing diameter of the nozzle (0.03 inch ≈ 0.762 mm) and focusing length of the nozzle (2.75 inch ≈ 69.85 mm).

Table 2. Machining parameters and their respective levels.

Machining Parameters	Symbols	Level		
		1	2	3
Pressure (MPa)	A	172	241	310
Abrasive-mass flow rate (g/s)	B	5.0	7.5	10.0
Standoff distance (mm)	C	4.0	3.0	2.0
Traverse rate (mm/s)	D	0.5	1.5	3.0

Table 3. Results of surface waviness in L_{18} OA and GRG

Run	A (MPa)	B (g/s)	C (mm)	D (mm/s)	Surface waviness (μm) at different cutting depths				GRG
					1.0	2.0	4.6	7.2	
					mm	mm	mm	mm	
1	172	5.0	4.0	0.5	9.35	6.58	10.61	7.38	0.6695
2	172	7.5	3.0	1.5	7.43	6.63	6.99	11.59	0.6973
3	172	10.0	2.0	3.0	9.25	6.83	12.46	19.57	0.5244
4	241	5.0	4.0	1.5	9.95	5.54	8.43	10.28	0.6872
5	241	7.5	3.0	3.0	6.80	6.54	10.43	13.84	0.6477
6	241	10.0	2.0	0.5	5.85	4.88	5.50	8.09	0.9330
7	310	5.0	3.0	0.5	6.62	5.81	7.77	8.67	0.7809
8	310	7.5	2.0	1.5	6.08	4.98	6.84	8.57	0.8739
9	310	10.0	4.0	3.0	9.76	7.51	10.10	12.89	0.5667
10	172	5.0	2.0	3.0	8.56	7.58	11.68	19.06	0.5259
11	172	7.5	4.0	0.5	9.38	7.61	7.80	9.00	0.6488
12	172	10.0	3.0	1.5	7.00	7.15	10.64	11.45	0.6437
13	241	5.0	3.0	3.0	8.05	8.09	10.67	20.84	0.5266
14	241	7.5	2.0	0.5	5.61	6.25	7.24	7.23	0.8415
15	241	10.0	4.0	1.5	7.66	7.59	8.20	9.16	0.6748
16	310	5.0	2.0	1.5	7.27	6.66	10.25	10.87	0.6612
17	310	7.5	4.0	3.0	10.19	6.59	7.73	8.47	0.6753
18	310	10.0	3.0	0.5	5.44	5.05	7.84	7.53	0.9010

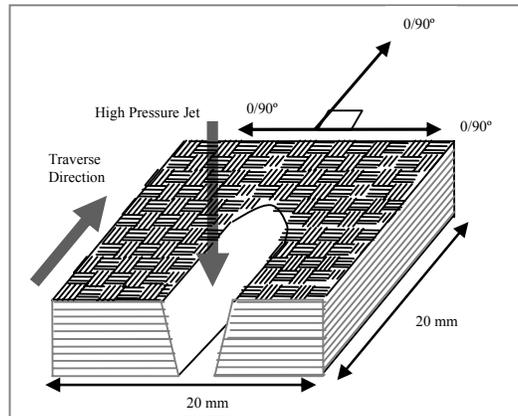


Fig. 1. Illustration of AWJ cutting on Kevlar laminate

A surface waviness measuring device, SURFPAK SV-514, equipped with a cone-shaped diamond stylus having the diameter of 10 μm and tip angle of 90° was used in this study. The measurement of surface waviness of each machined specimen was obtained at four measurement depths cut viz. 1.0 mm, 2.0 mm, 4.6 mm and 7.2 mm. Due to the variability of surface finish data, multiple measurements were taken of each surface evaluated so that averages could be calculated. All measurements were acquired using 0.8 mm cut-off length.

OPTIMIZATION OF MULTIPLE PERFORMANCE CRITERIA

Taguchi approach is not designed to optimize multiple response characteristics. It is used for optimizing single response characteristic. The lower-the-better characteristic for one factor may affect the performance other factors since other factors may demand higher-the-better characteristics (Deng 1989). In present study, the use of orthogonal array with the Grey relational analysis (GRA) optimization methodology for multi-response optimization is discussed. The grey-Taguchi method has been applied to optimize multiple performance responses of end milling process (Kopac and Krajnik 2007), electro discharge machining process (Lin and Lin 2005) and arc welding process (Tarng et al. 2002). The optimization of the process includes the following steps:

- (a) Normalizing the experimental results of surface waviness at four different depth cuts.
- (b) Calculating the Grey relational coefficients (GRC).
- (c) Averaging the Grey relational Coefficients to calculate the Grey relational grade.
- (d) Analyzing the experimental results using the grey relational grade
- (e) Selecting the optimal levels of process parameters
- (f) Verifying the optimal parameters setting through the confirmation experiment

RESULT AND DISCUSSION

GREY RELATIONAL ANALYSIS

The first step of GRA is the linear normalization of DOE data according to the type response. In the context of Taguchi methodology, surface waviness is the lower-the-better performance response. The normalized experimental results χ_{ij} can be expressed as:

$$\chi_{ij} = \left(y_{ij} - \min_j y_{ij} \right) \div \left(\max_j y_{ij} - \min_j y_{ij} \right) \quad (1)$$

where y_{ij} is the i th experimental results in the j th experiment. Larger normalized results correspond to the better performance and the best normalized result should be equal to 1 (Deng 1989). The normalized values are ranged between zero and one. The larger values yield better performance and the ideal value should be equal to one.

Next, the Grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be expressed as:

$$\xi_{ij} = \left(\min_i \min_j |x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}| \right) \div \left(|x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}| \right) \quad (2)$$

Where x_i^o is the ideal normalized result for the i th performance characteristics. ζ is the distinguishing coefficient which is set between zero and one; in our case it was set to $\zeta = 0.9$. The grey relational grades are calculated by averaging GRCs for each performance characteristic. The GRG values are tabulated in the last column of Table 2 The higher the GRG represents that the experimental result is closer to the ideally normalized value (Lin and Lin 2005). In the present work, experiment 6 has the best multi response characteristics amongst the 18 experiments conducted.

The mean GRG for each level of the machining parameters can be calculated by averaging the GRG based on OA as shown Figure 2. The optimal process parameter level yields the highest particular GRG in Figure 2. The optimal machining parameter setting is A3B2C3D1 or maintaining pressure at level 3 (310 MPa), level 2 for abrasive mass flow rate (7.5 g/s), level 3 for standoff distance (2 mm) and level 1 traverse rate (0.5 mm/s).

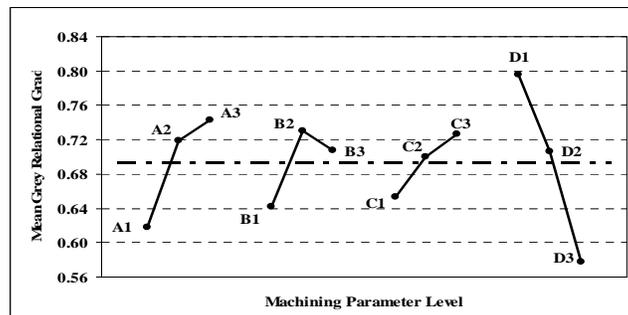


Fig. 2 Grey relational grade plot

CONFIRMATION TEST

The confirmation tests were conducted using the optimum combinations of machining factors. These confirmation tests were used to predict and verify the improvement in the quality characteristics for machining of Kevlar/phenolics composites with respect to the chosen initial parameter setting. The predicted Grey relational grade $\hat{\alpha}$ using the optimal level of the machining parameters can be calculated as (Lin and Lin 2005):

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^q (\alpha_i - \alpha_m) \quad (3)$$

where α_m is the total mean of the Grey relational grade, α_i is the mean of the Grey relational grade at optimal level and q is the number of the machining parameters. Table 4 shows the comparison of the predicted and actual machining performance for R_a using their respective optimal cutting parameters. The improvement in grey relational grade is 0.1673. The predicted Grey relational grade using optimal cutting parameters (0.9164) is comparable to the actual machining performance (0.8618). It is clearly shown that the surface waviness for four different depth cuts is greatly improved through this approach.

Table 4 Result of the confirmation experiment for R_a

	Initial cutting parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	A2B2C2D2	A3B2C3D1	
Depth Cuts	R_a (μm)	R_a (μm)	
1.0 mm	6.63	6.10	
2.0 mm	6.40	5.97	
4.6 mm	11.3	5.68	
7.2 mm	9.77	7.36	
GRG	0.6945	0.9164	0.8618

CONCLUSIONS

The use of the OA with GRA to optimize the AWJM process with multiple performance characteristics has been successfully reported in this paper. Optimization of multiple performance characteristics was simplified through this approach. The experimental result for the optimal setting shows that there is considerable improvement in the process. It is shown that the performance characteristics of the AWJM process namely hydraulic pressure, abrasive mass flow rate, standoff distance and traverse rate are improved together by using this method.

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